Irrigation Intensification or Extensification Assessment Using Spatial Modelling in GIS

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EXTENDED ABSTRACT

Land suitability assessment (LSA) plays an important role in maintaining and developing land use on a spatial basis. It identifies the levels and geographical patterns of biophysical constraints and evaluates potential capacity of land and its sustainable use. This paper describes the evaluation of land suitability for intensification (achieving more per unit of inputs) or extensification (retiring unsuitable lands) in irrigated cropping within the framework of a research project carried out at in Macintyre Brook catchment, southern Queensland, Australia. It presents a spatial modelling procedure for the assessment of irrigated cropland suitability using available biophysical information in a GIS environment. Spatial data, including topography (25 m resolution DEM), soils and groundwater, were converted into grid layers which were classified into four suitable levels based on threshold values of evaluation criteria defined by experts. A weighting coefficient of each criterion was determined using GIS-based analytical hierarchy process (AHP). All criterion maps were integrated as inputs to a GIS-based LSA tool, a spatial weighted-linear model, built with ArcGIS 9.2 software. The modelling exercise revealed that the spatial model produced fine discrimination of land units and there was a good potential of land use by intensifying irrigation in areas classified as highly suitable for irrigated cropping to optimum utilisation. The model output includes a land suitability map (Figure 0) which was then compared with the available catchment scale present land use map (50 m resolution) to decide the areas of irrigation intensification or extensification.

Application of the methodology showed the significance of spatial modelling for detailed mapping purposes at a comparatively low cost. Results of the study indicated the usefulness of spatial modelling in assessment of land suitability and land-use planning. The resultant map can assist decision makers in ensuring that lands are used according to their capacity to satisfy human needs for present and future generations, thus sustaining ecological and economic productivity of natural resources. Further modelling studies are being conducted for more detailed assessment of land use for different irrigated crops in this area.

The investigation presented in this paper is a biophysical evaluation, the selection of criteria was largely limited by data availability, and the threshold values of criteria are subjective as well. It was carried out without considering the uncertainty in the input data and expert knowledge. It is recognised that more parameters are required in the assessment of land characteristics on a catchment system, particularly those related to the properties that govern runoff, salinity and irrigation. Therefore, the study only gives primary results based on topography, groundwater, and soil properties that affect the suitability classification of irrigated cropping.

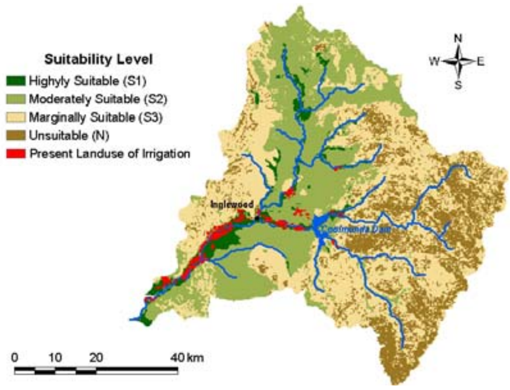

Figure 0. An evaluation map of irrigated cropland suitability in Macintyre Brook Catchment.

1. INTRODUCTION

Land suitability assessment (LSA) is the evaluation and classification of specific areas of land in terms of their ability to support a defined use. Land suitability assessment is critical to landuse planning. From a land use planning perspective, the systems of land use should be well matched with the inherent characteristics of the land to ensure long-term productivity and sustained use of the land. LSA is thus a process of estimating the potential of land for alternative kinds of land use, among which agricultural landuse may be the most important area where LSA is applied, especially in irrigation regions where intensification (enhanced productivity through greater application of water and other inputs per unit area) or extensification (retirement of area under irrigation) of irrigated cropping area, is needed to meet the production demands.

Land suitability involves integration of information from various sources. There are many criteria, both qualitative and quantitative, upon which land suitability depends. LSA is, therefore, a multiple criteria decision-making (MCDM) process. The attributes of land suitability criteria are to be derived from both spatial and non-spatial information under diverse conditions. Geographic information systems (GIS) are best suited for handling a wide range of data from different sources for a quick and cost-effective assessment.

The irrigation intensification is the process of *producing more agricultural produce from an ever-reducing area of land*. In common terms this definition is often verbalized in the slogans *"double productivity from half of the land area!"* and *"more jobs or crop per drop!"* Under many intensification scenarios in water-limited environments, land will have to be retired from irrigation. This process is captured under the term *extensification* and in itself can create management problems such as salinisation, and weed and pest control, and can result in socio-economic changes in a region. Both the irrigation intensification and extensification need to be based an objective spatial land suitability assessment.

Landuse suitability assessment (LSA) mapping and modelling is one of the most useful applications of GIS for spatial planning and management. The GIS-based multi-criteria evaluation procedures involve a set of geographically defined basic units (e.g. polygons in vectors, or cells in rasters), and a set of evaluation criteria represented as map layers. The problem is to combine the criterion maps according to the attribute values and decision maker's preferences using a set of decision rules in order to classify each unit into a suitability level.

Over the last decade or so, a number of multi-criteria evaluation methods have been implemented in the GIS environment (Carver 1991; Pereira and Duckstein 1993; Jankowski 1995, Tkach and Simonovic 1997, Malczewski 1999, Bojorquez-Tapia *et al.* 2001, Joerin *et al.* 2001, Malczewski 2004, Makropoulos and Butler 2005, Malczewski 2006). The two most widely used procedures are the weighted linear combination (WLC) and the Boolean overlay operations (such as intersection (AND) and union (OR). There are, however, some fundamental limitations associated with the use of these approaches in a decision making process mainly due to lack of theoretical foundation in deciding the weights which are often rather arbitrarily assigned without taking comparison among the criteria and classes into consideration. This limitation can be removed by using the Analytical Hierarchy Analysis (AHP) method (Saaty 1977, Saaty 1980, Saaty and Vargas 1991). AHP is a popular means of multi criteria technique which has been incorporated into the GIS-based landuse suitability procedures (Marinoni 2004). It calculates the needed weighting factors by the help of a preference matrix where all identified relevant criteria are compared against each other with reproducible preference factors. The APH gained high popularity because of easiness in obtaining the weights and capacity to integrate heterogeneous data, and therefore, it is applied in a wide variety of decision making problems. Given the wide variety of MCDM rules, it is hard to judge which of the methods is best in a particular situation. It is suggested that two or more methods should be used to dilute the effect of technique bias (Carver 1991).

This paper presents some results from a trial study of irrigated cropland suitability assessment at a catchment scale using spatial modelling in the ArcGIS environment. The objective of this study is to develop a methodology which identifies the levels and geographical patterns of biophysical constraints and hence, irrigated cropland suitability for maintaining and developing irrigated cropping landuse. A simple approach which integrates the AHP, WLC and the Boolean overlay operations into GIS-based multi-criteria evaluation procedures, in terms of a LSA model, is developed and tested to achieve a rapid assessment of determining areas of irrigation intensification or extensification in Macintyre Brook Catchment, Queensland, Australia.

2. METHODOLOGY

2.1. Study Area

The Macintyre Brook Catchment is situated in southern QLD near the state border with NSW, and lies between 27°57’01’’S and 28°47’48’’S latitude, and 150°45’05’’E and 151°42’ 24’’E longitude. The major town Inglewood is located 260 km southwest from Brisbane. The catchment is relatively flat in the western area, with undulations becoming steeper towards east and northeast. The Elevation at Inglewood is 284 m. Macintyre Brook, which flows from east to west, and their tributaries are the main source of surface water. The region is not well endowed with groundwater. Coolmunda Dam supplies irrigation water to Macintyre Brook along which the main irrigation areas of the catchment are located. Daily temperatures range from 18 to 32 °C in summer and 4 to 18 °C in winter, when frosts are common. Average annual rainfall is 650mm. Most of it falls between October and March, but around 100 mm falls in winter (Malcolmson and Lloyd 1977).

The catchment covers an area of 4,200 km^2. It is characterised by extremely diverse soil types and topography (Harris 1986), making it suitable for a wide variety of landuse and rural production. Currently about 1.5 percent of the catchment area is devoted to irrigated cropping and perennial horticulture, as well as sown pastures. The remainder is dominated by dryland cropping (3%), native pasture grazing country (80%) and State Forest Reserves (15%). Historically, grazing was predominant but dryland and irrigated cropping have become increasingly significant over time. The main crops include fodder (lucerne), maize, sorghum, peas, and orchard such as peach, plum and apricot.

The area under irrigation in the catchment has increased steadily following the construction of the Coolmunda Dam in 1968. Irrigation in the region was traditionally geared around tobacco production, but the demise of that industry in the 1960s led many irrigators to fall back on opportunistic irrigation of pastures and crops. More recently there has been significant development in olive and peanut production. The region is also well suited to stone fruits, citrus, pecan nuts, herbs, a wide variety of vegetable crops, grapes and aquaculture.

2.2. Derivation of Criterion Maps

Irrigated cropland suitability analysis at a catchment scale is an interdisciplinary approach by including the information from different sources such as climate, topography, soils, groundwater and irrigation. Each of these components consists of many factors which affect evaluation results, e.g. physical and chemical properties of soil, as well as quantity and quality of groundwater. As early as 30 years ago, the Food and Agricultural Organisation (FAO 1976) proposed an approach for land suitability evaluation in terms of suitability ratings from highly suitable to not suitable based on the suitability of land characteristics to different crops. The suitability classes used in this study were adapted from the structure of FAO system considering four levels: highly suitable (S1), moderately suitable (S2), marginally suitable (S3) and unsuitable (N). Selection of evaluation criteria in this study were based on project objective, spatial scale, and in particular, data availability. Five criteria were chosen, including slope (S), soil texture (ST), depth to water-table (DTW), electrical conductivity of groundwater (ECw), and hydraulic conductivity of soil (Ks). The threshold values of evaluation criteria for each of the four suitability classes were determined based on literature survey and expert opinions (Table 1). It should be noted that some of these criteria might be interdependent when used for determining the suitability classes (e.g. depth and salinity of the groundwater, or soil texture and hydraulic conductivity). The threshold values are therefore subjective and they are only applicable to broad scale analysis of irrigated cropping in the catchment. Table 1 provides the fundamental basis to construct the criteria maps (one for each factor).

Table 1. Criteria for suitability assessment of irrigated croplands.

	S1*	S2*	S3*	N*
S (%)	0-2	2-4	4-8	>8
ST	fine to medium texture	heavy clay	coarse or poorly drained	very coarse or shallow depth
DWT (m)	>4	3-4	2-3	<2
ECw (ds /m)	0-.5	.5- 2	2-5	>5 (if depth <4m)
Ks (m/d)	.3-1	.05-.3 or 1-2	2-2.5	<.05 or >2.5

* S1 = highly suitable; S2 = moderately suitable; S3 = marginally suitable; and N = unsuitable

Spatial data were converted into raster layers and projected into UTM Zone56 in ArcGIS 9.2. Slopewas generated from a 25 m resolution DEM. The other four datasets were also resampled to 25m cell size using a cubic convolution algorithm. They were then classified into four classes as integer rasters representing different suitability levels based on the threshold values assigned to them in Table 1. They are the input data to the GIS-based LSA model. Given these criterion maps, the problem is to combine the maps so that the suitable level for each cell can be classified. The key of this combination procedure is identifying the weight of criterion importance, in other words, the weight of each criterion map.

2.3. Application of GIS-based LSA Model

A GIS-based LSA tool with a built-in AHP module (Marinoni, 2004) was adapted to weight the criterion maps in ArcGIS9.2 environment. First, the relative importance of each criterion was determined before weighting each of the relevant criteria. All criteria were compared against each other in a pairwise comparison matrix which is a measure to express the relative preference among the factors. The values of the comparison were determined according to the scale introduced by Saaty (1977; Table 2). The available values for the comparison are the member of the set: {9, 8, 7, 6, 5, 4, 3, 2, 1, 1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9}, with 9 representing absolute importance and 1/9 the absolute triviality (Saaty 1980, Saaty and Vargas 1991). This approach required the experts to provide their best judgment to the relative intensity of importance of one evaluation factor (criterion) against another. After careful analysis of the set of five evaluation criteria/factors in the study area, a numerical value showing relative importance (preference or dominance) of each criterion was assigned into a matrix (Table 3) where, for example, slope has been regarded slightly more important than criterion soil texture, hence a value of 2 has been assigned to the

Table 2. Scale for pair-wise comparisons (Saaty and Vargas, 1991).

Intensity of Importance	Description
1	Equal importance
3	Moderate importance of one factor over another
5	Strong or essential importance
7	Very strong or demonstrated importance
9	Extreme importance
2, 4, 6, 8	Intermediate values
Reciprocals	Values for inverse comparison

Table 3. A pair-wise comparison matrix describing the relative preference among identified criteria.

	Slope	ST	DTW	ECw	Ks
Slope	1	2	4	3	1/3
ST	1/2	1	5	4	1/2
DTW	1/4	1/5	1	1/2	1/4
ECw	1/3	1/4	2	1	1/3
Ks	3	2	4	3	1

corresponding matrix position. The transpose position automatically gets a value of the reciprocal value, in this case 1/2.

Next, the assigned preference values were synthesised to determine a ranking of the relevant factors in terms of a numerical value which is equivalent to the weights of the factors. Once the constructed matrix was entered into the GIS-based AHP module, the weighting coefficients of criteria were automatically derived before grid-computation for suitability evaluation (Table 4). The weights associated with criterion maps were then input into the model to generate the suitability map.

3. RESULTS AND DISCUSSION

The weighted criterion maps (Figure 1) were aggregated to produce a final suitability map (Figure 2) according to defined regulation in ArcGIS. The resultant map shows the extent distribution of the land suitability classes. The most suitable locations are in dark green, and the unsuitable lands are in dark brown. It can be clearly seen that the greenish areas coincide well with the areas where Ks ranges from 0.5 m/d to 2 m/d since this criterion received highest weight (about 39%) among the others. Therefore, we expect a high influence of classified Ks values in the result map. The DWT is almost uniform with values greater than 4 m in most of the catchment (Only a few local areas along Bracker Creek and Pariagara Creek are between 2-4 m). So this criterion has been assigned a smallest weight. ECw is a measure of groundwater salinity. It is either greater than 0.05 m/d, or less than 2.5 m/d in the catchment, which means the whole area is at least marginally suitable for irrigation. It also indicates

Table 4. The weights derived for criterion maps from GIS-based AHP module.

Criterion	Weight
Slope	0.2463
ST	0.2210
DTW	0.0571
ECw	0.0881
Ks	0.3874

that salinity is not a significant problem at present. Thus this criterion obtained a corresponding lower weight value. As a result, both DTW and ECw had no great impacts on the evaluation result.

The effects of soil texture on soil infiltration rate, and consequently the suitability level for irrigation, is critical. Unfortunately, we had no detailed quantitative data on this factor. So a relatively lower value was gained by this criterion. Slope is not only an essential factor, but also a reliable criterion derived from the high resolution DEM. It can generate fine discrimination of land units to delineate areas of different suitability levels for a detailed assessment. It accordingly received a high weighting factor. Both slope and soil texture produced relatively significant impacts on the resultant map.

For each suitability class, the percentage of area in the catchment is summarised in Figure 3. There is about 6% of total catchment area being classified as highly suitable (S1), unsuitable land covers about 14%, and moderately and marginally suitable classes represent 35% and 45% of land area respectively.

The S1 is found mainly on the flood plain of Canning Creek and the Macintyre Brook, and alluvial fans and flats of smaller streams where varying areas of land with better drained soils are suitable for cultivation. These potentially irrigable lands are made up of four soil types distinguished by texture which include alluvial sandy loam, alluvial silty loam, clay loam and sandy loam. Generally, most unsuitable areas were located in the east-southeast part of the catchment where the surface is undulating, soil texture is poor and soil hydraulic conductivity is very low. A large proportion of this land is under grazing pasture landuse, only a small portion of it is used for production forestry.

The suitability map and present landuse map were overlaid to identify differences and similarities between the present landuse and the potential landuse. The overlay revealed that, in the study area, a substantial portion (70%) of present irrigated cropland falls in the highly suitable class, while approximately 30% is in moderately suitable areas. There is only 1% under marginally suitable areas and none is under unsuitable regions. Highly suitable land (S1) should be retained for irrigation agriculture since limitations to irrigated cropping in S1 land can be overcome by standard management practices. Policies should be considered which protect this land from unnecessary and premature subdivision for urban

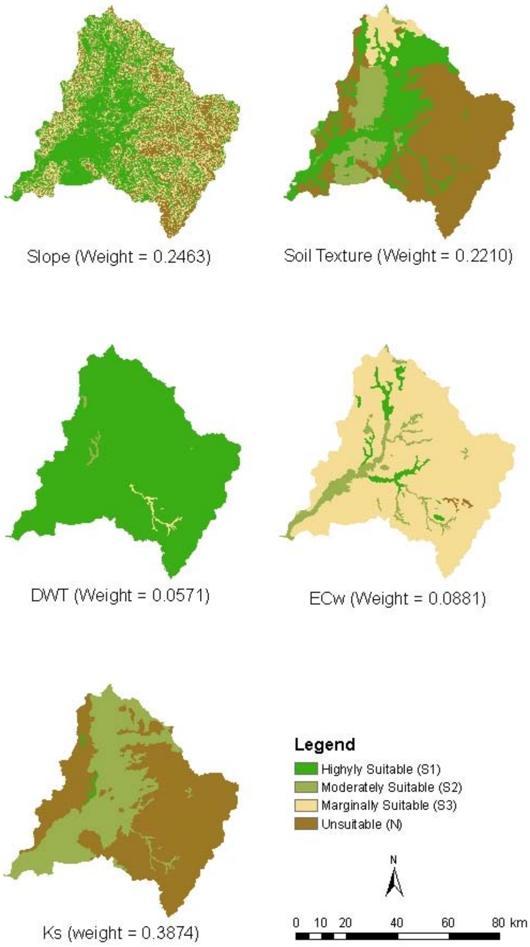

Figure 1. Criterion maps used as inputs to LSA model for the evaluation of irrigated croplands. The suitability levels are classified based on the threshold values in Table 1.

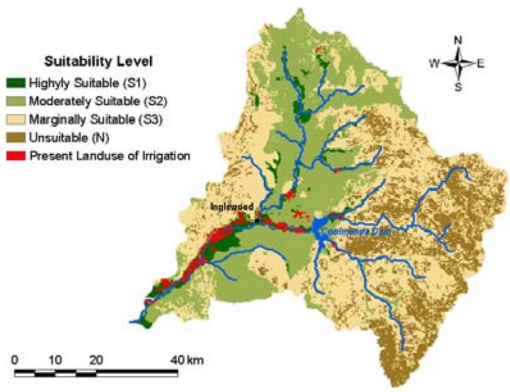

Figure 2. A evaluation map of irrigated cropland suitability in Macintyre Brook Catchment.

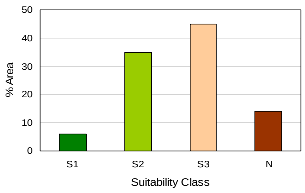

Figure 3. Percentage areas of each suitability classes against total catchment area.

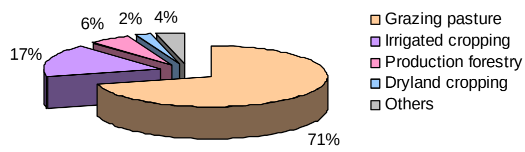

Figure 4. Percent areas of current landuse types on highly suitable (S1) lands.

or rural residential use or from alienation caused by other landuse such as roads. Limitations to irrigated cropping on moderately suitable land (S2) need to be recognised because a decline in productivity may occur and a range of landuse problems may develop if this land is used and managed inappropriately.

Figure 4 shows that currently only 17% of the total highly suitable lands have been used for irrigation which mainly distributed in the southwest part of the catchment. A large proportion (71%) of highly suitable land for irrigated cropping located in the north part of the catchment has been dominated by grazing pasture. Therefore, there is a great potential in cultivating more irrigated cropping if water is available, in other words irrigation intensification, in these highly suitable areas. On the other hand, according to Figure 2, there is no need for irrigation extensification in the unsuitable areas since there is no irrigation practice occurring on these lands.

Irrigated agricultural land suitability analysis is a prerequisite to achieve optimum utilisation of the available land resources for sustainable irrigated cropping production. According to FAO (1985), “some fifty million hectares of land could be developed for irrigated agriculture in the next twenty-five years. An even larger area needs rehabilitation or changes connected to intensified production. Irrigation developments are expensive and usually require investment and credit facilities, and mistakes are very costly. Therefore, almost all of this vast area will need to be evaluated to ascertain its suitability for the proposed irrigation systems.” The model and methodology employed in this attempt is a quick and practical way to fulfil this important task in a cost effective manner.

4. CONCLUSIONS

A GIS-based land suitability assessment model which integrates AHP module in it has been adapted and applied to a catchment scale irrigation intensification or extensification assessment. It has been found that this model is a valuable and user-friendly tool. In comparison to the conventional GIS-based combination approaches, it provided more flexibility and high efficiency for evaluating land suitability. The capability of it to generate and visualise a range of weighting results is particularly useful.

The overlay results obtained from comparison of resultant map against present landuse map indicated that most (99%) of existing irrigated cropping is located in highly suitable and moderately suitable lands in the southwest part of the catchment; and a significant proportion (71%) of highly suitable areas lie in the north part of the catchment where irrigation can be intensified.

The following points can also be drawn from this study:

(1) Selection of variables or criteria according to local conditions is crucial to land suitability evaluation. Criteria considered in the evaluation are also diverse and complex. GIS approach allows integration of the spatial variability of terrain and other relevant parameters. The merit of it is found to be beneficial in delineating areas of various suitability ratings for a detailed assessment.

(2) The determination of weighing factor for each criterion or variable is vital because they would directly affect the evaluation result. The AHP is one of suitable methods to do it. This approach is of particular importance for problems involving large number of variables represented by means of the raster data model, when it is impossible to perform a pairwise comparison of the criteria.

(3) The integration of spatial data and application of GIS-based multi-criteria evaluation procedures could provide a superior database and guide map for decision makers in order to achieve better agricultural production. The study is helpful in considering irrigated cropping management options for irrigation intensification or extensification.

Finally, this investigation is a biophysical evaluation, the selection of criteria was largely limited by data availability, and the threshold values of criteria are subjective as well. It was carried out without considering the uncertainty in the input data and expert knowledge. It is recognised that more parameters are required in the assessment of land characteristics on a catchment system, particularly those related to the properties that govern runoff, salinity and irrigation. Therefore, the study only gives primary results based on topography, groundwater, and soil properties that affect the suitability classification of irrigated cropping. Work is in progress in collecting more data which influence the sustainable use of the land, such as soil salinity, irrigation facilities and socio-economic factors. That may be later incorporated into the model described in this paper to ensure the adequate and detailed evaluation and classification of land suitability for different irrigated crops. In addition, future study will use GIS fuzzy MCDM approaches to reduce the effect of arbitrary class boundaries on the results, and conduct sensitivity analysis on criteria weightings.

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